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Life cycle assessment of Virginia mallow production with different fertilisation options

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ABSTRACT

Lignocellulosic crops can be a significant source of feedstock for the chemical industry. They can be grown on poorer soils, but fertilisation should be applied to achieve a considerable yield. The aim of the study was to determine the environmental impact of the production of Virginia mallow (*Sida hermaphrodita* Rusby L.) biomass fertilised with digestate: wet (WD), dried (DD) and torrefied (TD), obtained from an agricultural biogas plant and fertilised with mineral fertilisers (MF) and non-fertilised (C). All the fertilisers were applied at a rate equivalent to 85 and 170 kg ha^{-1} N. The system boundaries covered the production and use of digestate and mineral fertilisers, preparation of a field, growing Virginia mallow, harvest and transport of biomass from the field to the farm. The life cycle impact assessment of cultivation was done using the ReCiPe Midpoint method. The most beneficial effect on climate change was observed for utilisation of dried and torrefied digestate. The most adverse effect on human toxicity was observed when the TD was applied at both fertilisation rates. Higher particulate matter formation for all the growing options than for C resulted from production of fertilisers and use of machines. The lowest impact on terrestrial acidification was observed in the MF 85 option and the highest was in TD 170, which resulted mainly from high field emission. The use of digestates and mineral fertilisers resulted in an increased effect on freshwater eutrophication (30–56-fold). Torrefaction of digestate had the largest impact on terrestrial ecotoxicity. The greatest impact on fossil depletion was found for MF 170. The impact category with the highest normalized score was freshwater eutrophication. The production of Virginia mallow intended for bioproducts can fulfil the condition of low GHG emission. The application of fertilisation in all forms affected the environment more in the other impact categories than the base scenario. The application of WD 85, WD 170 and DD 85 could be recommended for Virginia mallow instead of mineral fertilisers, whereas DD 170 and TD at both rates had the most adverse environmental effect.

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1. Introduction

Dedicated lignocellulosic crops can be a significant source of feedstock for the chemical and energy industries. Lignocellulosic biomass can be turned into products by various methods, e.g. thermochemical, chemical or biochemical. It can be derived from forest resources and agriculture as well as from waste (Gupta and Verma, 2015; Krzyżaniak et al., 2016a; Kupecki et al., 2017; McKendry, 2002). Such plants as short rotation woody crops, grasses and perennial plants have been successfully grown, turned into chips, briquettes and pellets and subsequently used in the generation of heat and electricity (Brosse et al., 2012; Cardinael et al., 2012; Klasnja et al., 2002; Krzyżaniak et al., 2015; Manzone et al., 2014; Stolarski et al., 2014, 2016). These technologies are often competitive towards the production of energy from fossil fuels and annual energy crops, and they provide added value in the form of reduced environmental burden, especially in regard to

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greenhouse gas (GHG) emission (González-García et al., 2012; Jäppinen et al., 2014; Krzyżaniak et al., 2016b; Manzone et al., 2014; Manzone and Calvo, 2016; Stolarski et al., 2015). Production of second generation fuels and biomass-based products, whose carbon footprint is lower than that of fossil fuels, is in the development and commercial phase (González-García et al., 2011; Gupta and Verma, 2015; Karka et al., 2017; Karlsson et al., 2014; Krzyżaniak et al., 2016b; Meyer et al., 2016). In principle, lignocellulosic plants should be grown on lower quality soils, whose usability in growing food and fodder crops is lower; they can also be grown in degraded areas with regards to their reclamation as well as with a view to phytoremediation of contaminated soils (Gizińska-Górna et al., 2016; Grünewald et al., 2009; Krzyżaniak et al., 2015; Rockwood et al., 2004). Legislators in some countries as well as the EU legislation obligate energy producers to use agricultural biomass from such sources as straw and biomass derived from dedicated energy crop plantations. Such products should meet the requirements for renewable sources and they should be produced in a sustainable manner. According to Directive 2009/28/EC, GHG emission for biofuels produced from 1 January 2018 should be reduced by at least 60% (European Commission, 2009; Ministry of Economy, 2012).

It was therefore decided to determine the effect of the production of Virginia mallow (*Sida hermaphrodita* Rusby L.) on the environment by means of a life cycle assessment. At Department of Plant Breeding and Seed Production, University of Warmia and Mazury in Olsztyn, studies of Virginia mallow have been conducted since 2001 (Stolarski et al., 2005). Studies on the use of biomass of this crop have also been conducted in other countries of Europe (Franzaring et al., 2015; Šiaudinis et al., 2015). This species has been chosen because it can be grown in temperate climate zones. It can be used as a substrate in biogas plants and, for this, two biomass harvests are possible during the growing season. Owing to a high cellulose content, Virgina mallow can also be used in the production of biofuels and other products obtained from cellulose. Its biomass is also used for the production of solid fuels (briquettes and pellets). Other advantages of the crop include the possibility of its cultivation on lower quality soil and no need for using pesticides (Stolarski et al., 2005; Franzaring et al., 2015; Nabel et al., 2016). Studies have shown that Virginia mallow grown in Poland yields 9.4–12.2 Mg ha^{-1} d.m. (Jankowski et al., 2016; Tworkowski et al., 2014). Furthermore, the average yield of the crop obtained in a study conducted in Lithuania ranged from 4.7 to 7.5 Mg ha^{-1} d.m., with the maximum level reaching 8.1 Mg ha^{-1} d.m., with a level of nitrogen fertilisation of 120 kg ha^{-1} N (Šiaudinis et al., 2015). Crops (including Virgina mallow) should be fertilised in order to ensure an economically and technologically reasonable biomass yield. To this end, it was decided that residue (digestate) from biogas production would be used instead of expensive and energy-intensive mineral fertilisers. Between 30 and 60% of the weight of substrates at a biogas plant is not digested and it turns into digestate, which is rich in nitrogen and phosphate. Digestate is also rich in organic matter, which increases the content of organic carbon in poorer soils and improves the stability of crop yield. This makes digestate a valuable organic fertiliser with positive effects on the soil organic matter status and on the availability of nutrients for the crop (Corré and Conijn, 2016). There were over 17,500 biogas plants in Europe in 2014. Over 2.4 million Mg of substrates were used in the production of biogas in Poland alone; this resulted in the production of considerable amounts of digestate. Its excess can be used to fertilise energy crops, to increase the content of organic carbon in soil and to improve the soil quality (European Biogas Association, 2015; Agencja Rynku Rolnego, 2016; Wolf et al., 2014). The aim of the study was to determine the environmental effect of the production of Virginia mallow biomass fertilised with digestate obtained from an agricultural biogas plant and fertilised with mineral fertilisers compared to the "no fertilisation" option.

2. Methods

In order to determine the environmental impact of the production of Virginia mallow for a biorefinery, the study methodology was based on the standards: ISO 14040 "Environmental management—Life cycle assessment—Principles and framework" and ISO 14044 "Environmental management—Life cycle assessment—Requirements and guidelines" (European Committee for Standardisation, 2006a; European Committee for Standardization, 2006b). A life cycle assessment was done using the SimaPro software.

2.1. Goal, scope and functional unit

The aim of the study was to determine the environmental impact of the production of Virginia mallow biomass fertilised with digestate: fresh (wet) (1), dried (2) and torrefied (3), obtained from an agricultural biogas plant; and fertilised with mineral fertilisers (4) and not fertilised (base scenario - control) (5). An attributional approach was used for our analysis. The research system boundary "from cradle to farm gate" was adopted. 1 Mg of dry biomass was taken as a functional unit (FU) for chemical industry (e.g. production of polymers, bioethanol). 1 GJ of energy from fresh biomass was taken as a functional unit for production of energy or biofuels (for estimates of GHG emission).

2.2. System boundaries

The system boundaries (Fig. 1) covered the co-production of digestate from a biogas plant which uses a substrate comprising 50% of cattle manure and 50% of pig manure. The boundaries included the production of fertilisers from digestate and the production of mineral fertilisers. Agricultural operations included preparing a field, growing Virginia mallow, harvest and transport of biomass from the field to the farm (from cradle to farm gate), and gathering related materials (e.g. herbicides, fuels and planting material) for a life cycle inventory. The plantation lifetime was assumed to be 15 years. After that period, it was shut down by mechanical means in order to restore the original use of the land (arable land). The study also included an analysis of field emissions of GHG (including change of soil organic carbon), NH_3, NO_x, non-methane volatile organic compounds (NMVOC), particulate

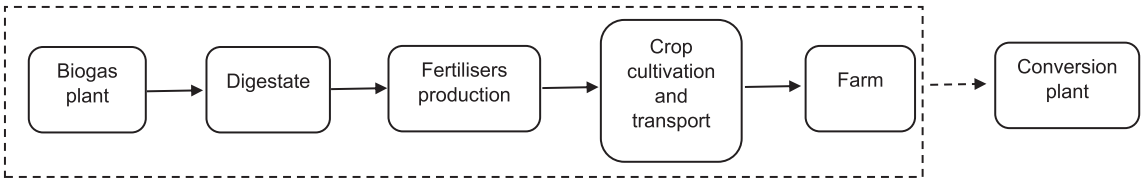

Fig. 1. System boundary of herbaceous crop cultivation, harvest and transport.

Table 1
Data for field operation.

Operation	Diesel (kg ha^{-1})	Material	Comments
Work of setting up a plantation and its liquidation is done once in the entire period of the plantation use (once per 15 years)			
Spraying	2.04	Glyphosate. Roundup 360 SL, 5 l ha^{-1}	
Disking	8.98		1 x coverage
Winter ploughing	29.30		5–ridge plough. ploughing depth 30 cm
Harrowing (x2)	11.20		2 x coverage
Planting with a planting machine	14.06	20,000 rhizomes ha^{-1}	4-row planting machine
Weeding (3x)	21.09		3 x coverage
Liquidation of plantation	44.65		5–ridge plough. ploughing depth 30 cm
Work done every year			
Wet digestate fertilisation	19.68–39.36	Wet digestate	input varies depending on the fertiliser rate
Dry and torrefied digestate fertilisation	7.03–14.06	Dry or torrefied digestate	input varies depending on the fertiliser rate
Mineral fertilisation N PK	7.02	Ammonium nitrate, triple superphosphate, potassium salt	The same time for a smaller and higher fertilisation rate
Soil loosening and mixing of fertilisers	12.65		1 x coverage applied
Harvesting	11.25–73.84		depending on the yield
Field transport	27.0–173.58 (tkm)[a]		depending on the yield

[a] Input in tonne × kilometre (tkm) units.

matter to the atmosphere as well as N and P leaching. A detailed description of the system boundaries is presented in the following subchapters.

2.3. Modelling and data sources

2.3.1. Cropping system

Data for life cycle inventory (LCI) of the cropping system was obtained from field studies conducted in 2013–2015 at the Didactic and Research Station in Łężany, in the north-east of Poland (53°59′ N, 21°09′ E), owned by the University of Warmia and Mazury in Olsztyn. The experimental plot was situated on soil formed from sandy loam, on land with a slope not exceeding 2%. Data for the life cycle inventory were collected from average values from three years of the study (2013–2015).

Outlays were determined and results were gathered for the cultivation of Virginia mallow (*Sida hermaphrodita* Rusby L.). Virginia mallow rhizomes were planted at a density of 20 thousand ha^{-1}. The field was prepared with agricultural operations carried out once (setting up and liquidation of the plantation) including: spraying with glyphosate, disking, winter ploughing, harrowing (2x), planting, mechanical weeding (3x) and liquidation of plantation. Operations carried out every year, throughout the plantation life cycle (15 years), included: fertilisation, soil loosening and mixing fertilisers, harvesting and transport (Table 1).

Various fertilisation options were applied. The following were used: wet digestate (WD); dry digestate (DD); torrefied digestate (TD) and mineral fertilisation (MF). The experiment with no fertilisation was taken as the base scenario (control) (C). Fertilisation rates at two levels were calculated based on the content of nitrogen in organic fertilisers: 85 and 170 kg ha^{-1} N (Table 2), so the amount of P and K in the fertilisers was different for different fertilisers and different application rates of N. Nitrogen assay was conducted by Kjeldahl's method according to the EN 16169:2012 standard. The content of phosphorus was determined by the spectrophotometric method according to EN 14672:2005 and EN ISO 6878:2004 standards. Potassium was assayed by the flame photometry method according to the PN-Z-15011–3:2001 standard. Mineral fertilisation with nitrogen was also applied at two rates of 85 kg and 170 kg ha^{-1} N as ammonium nitrate. Mineral fertilisation with phosphorus (triple superphosphate) and potassium (potassium salt) was the same in both cases: 30 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} K_2O. The yield from 15 years of cultivation is shown in Table 3.

2.3.2. Production of fertilisers

The study system boundary covered the production of digestate in a biogas plant. The data were modified for the study from the EcoInvent database. The modification involved allocation between two products: biogas and digestate based on their economic value: 95% for biogas and 5% for digestate.

Another element was the production of fertilisers from digestate based on experiments conducted at the UWM. Wet digestate containing 5.7% of dry matter with no further processing was used as a fertiliser. Wet digestate (WD) was used to produce dry digestate (DD). To this end, wet digestate was dehydrated on an auger separator and then dried in a pipe reactor until a dry matter content of 92% was achieved. The dried digestate was then used to obtain torrefied digestate (TD) with a dry matter content of 97%.

Mineral fertilisation was an alternative to organic fertilisers obtained from digestates. To this end, processes for the production of ammonium nitrate (34% N), triple superphosphate (48% P_2O_5) and potassium chloride (60% K_2O) from EcoInvent database were taken into account.

2.3.3. Field emissions

Field emissions of GHG (CO_2 eq.) are the sum of emissions of CO_2 linked with a change of soil organic carbon (SOC) content as well as direct and indirect emission of N_2O caused by nitrification and denitrification of nitrogen compounds.

SOC change was calculated from the net C input to the soil. Net C

Table 2
Average amounts of organic and mineral fertilisers applied, equivalent to the rate of N of 85 and 170 kg ha^{-1} in organic fertilisers and energy sources for their production.

Form of fertilisation	Level of N fertilisation (kg ha^{-1})		Energy source
	85 N	170 N	
Wet digestate (1000 dm^3)	26.0	52.0	Mix of non-renewable and renewable energy sources (allocation from biogas production)
Dry digestate (Mg)	5.4	10.8	Same as in WD +, electricity from biogas, heat from biogas engine
Torrefied digestate (Mg)	5.6	11.2	Same as in WD and DD + heat from biomass

Table 3
Yield of Virginia mallow (Mg ha^{-1} d.m.) during the life cycle of a plantation, depending on the method and level of fertilisation.

Fertilisation	N Level (kg ha^{-1} N)	Yield of biomass (Mg ha^{-1} d.m.)	Energy yield (GJ ha^{-1})
Wet digestate (WD)	85	44.4	775.5
	170	73.8	1279.5
Dried digestate (DD)	85	70.1	1240.5
	170	86.7	1530.0
Torrefied digestate (TD)	85	54.5	970.5
	170	67.4	1201.5
Mineral fertilisers (MF)	85	73.1	1285.5
	170	83.1	1479.0
Control (C)	0	42.9	768.0

input was calculated as the difference between organic carbon (OC) available to the soil from Virginia mallow and a reference crop (spring barley with straw incorporated into soil) (Parajuli et al., 2017a, 2017b). Crop residues and digestates were a source of OC. Net C input was calculated from the formula:

$$\text{Net C input} = C_{above_Vm} + C_{below_Vm} + C_{digestate} - C_{above_Ref} - C_{below_Ref}$$

where: C_{above_Vm}, C_{above_Ref} – the above-ground carbon in crop residues, respectively: Virginia mallow and the reference crop (kg ha^{-1} C); C_{below_Vm}, C_{below_Ref} – the below-ground carbon in root residues and exudates, respectively: Virginia mallow and the reference crop (kg ha^{-1} C); $C_{digestate}$ – amount of carbon in the digestates used (kg ha^{-1} C).

The OC introduced to soil with crop residues was calculated by the method used in the C-TOOL method from the formulae:

$$C_{above} = (1/\alpha - 1 - \delta\zeta)\varepsilon Y$$

$$C_{below} = \{\beta/[(1-\beta)\alpha]\}\varepsilon Y$$

where: α – harvest index of main crop product relative to above-ground biomass; β – root biomass and exudate carbon (below-ground C) as proportion of yield of main crop product; δ – biomass of secondary crop product as proportion of yield of main crop product; ζ – proportion of secondary crop product that is harvested; ε – concentration of C in biomass (kg Mg^{-1} C); Y – yield of main crop product (Mg ha^{-1} d.m.) (Taghizadeh-Toosi et al., 2014).

The average yield of spring barley in Poland was adopted in the calculations; it was 3.51 Mg ha^{-1} during the period between 2013 and 2015 (Central Statistical Office of Poland, 2015), whereas the yield data for Virginia mallow were obtained from our field experiment. The α and β parameters of model C-TOOL for spring barley were: 0.45 and 0.17, respectively. The δ parameter was 0 (barley straw was not collected). The carbon content in barley biomass (ε) was taken as 460 kg C Mg^{-1} d.m. The model parameters for Virginia mallow were estimated from the parameters defined for model C-TOOL for grass and grass-clover and for maize for silage. The α and δ parameters were taken as: 0.80 and 0.00, respectively. Like other perennial herbaceous crops, since Virginia mallow has a well-developed root system (Chimento et al., 2016; Barbosa et al., 2014), the β parameter was taken as for perennial grasses (0.45). The carbon content in Virginia mallow (ε) and in digestates was determined with the use of an elemental analyser ELTRA CHS 500 (ELTRA GmbH, Germany).

Emissions of CO_2 due to SOC change were calculated in a 100-year perspective. It was assumed that only 9.7% of organic carbon introduced to soil (plant residues and organic fertilisers) is permanently sequestered during the assumed time period (Petersen et al., 2013).

Emissions of N_2O were calculated by the method recommended by IPCC (Eggleston et al., 2006). Transformations in the soil of N from mineral and organic fertilisers, from crop residues (above-ground and below-ground), as well as from N mineralisation associated with loss of soil organic matter were taken into account in calculations of the direct emission of N_2O. The R_{AG} (ratio of above-ground residues dry matter to harvested yield d.m. for crop) and the R_{BG} (ratio of below-ground residues dry matter to harvested yield d.m. for crop) coefficient for Virginia mallow adopted in the current analysis were equal to: 0.25 and 1.02, respectively. They correspond to parameters of model C-TOOL, which were used in the analysis of SOC changes. Calculations of indirect emission of N_2O included emissions outside the field, but were related to the nitrogen in fertilisers and nitrogen from crop residues, which was emitted to the atmosphere as NH_3 and NO_x and was leached. The default N_2O emission coefficient from N leaching was 0.0075, and 0.01 kg N_2O-N kg^{-1} N for the other nitrogen sources (Eggleston et al., 2006). The nitrate leaching was calculated by the field N-balance method recommended by many authors (Alaphilippe et al., 2016; Parajuli et al., 2017a, 2017b). Nitrate leaching (N_L) was calculated from the formula:

$$N_L = N_F + N_{AD} + N_{SOM} - N_{uptake} - N\text{-}NH_3 - N\text{-}NO_x - N\text{-}N_2O_{direct} - N\text{-}N_{2denitr}$$

where: N_F – nitrogen supplied with mineral or organic fertilisers (kg ha^{-1} N), N_{AD} – nitrogen atmospheric deposition (3.8 kg ha^{-1} N in 2013–2015) (Chief Inspectorate Of Environmental Protection, 2017), N_{SOM} – the net annual amount of N mineralised in soils as a result of loss of soil carbon (kg ha^{-1} N), N_{uptake} – nitrogen present in the yield (kg ha^{-1} N), N-NH_3, N-NO_x, N-N_2O_{direct}, N-$N_{2denitr}$ – soil emission of gas (NH_3, NO_x, N_2O, N_2) resulting from the application of fertilisers and from decomposition of crop residues (kg ha^{-1} N).

The net annual amount of N mineralised in soils was calculated from the formula (Eggleston et al., 2006):

$$N_{SOM} = \Delta C_{mineral}/R$$

where: $\Delta C_{mineral}$ – SOM depletion (kg ha^{-1} C), R – C:N ratio in soil, which was 15.0 ± 1.9 in the current study. It was similar in other studies conducted in the north-east of Poland (Smólczyński et al., 2011).

N_{uptake} was calculated from the yield of Virginia mallow and nitrogen content in biomass. Emission of NH_3 and NO_x was calculated by the factor method (European Environment Agency, 2016). The NH_3 emission index for ammonium nitrate and digestates (organic waste) was: 0.016 and 0.08 kg NH_3 kg^{-1} N_{input}, respectively. Emission of NH_3 from crop residues was also taken into account by the method described by Ruijter and Huijsmans (2012). The NO_x emission factor was 0.04 kg NO_2 kg^{-1} N_{input} for all types of fertilisers (European Environment Agency, 2016). N_2 emission from nitrogen denitrification was calculated based on the SimDen model (Vinther, 2005). Emission of phosphates caused by the leaching from mineral fertilisers was taken at 1% PO_4^{3-} per kg P applied (Iriarte et al., 2010).

Emissions of other substances to the atmosphere were also taken into account in the analysis. The following emission factors were adopted for NMVOC, PM10 and PM2.5: 0.86, 1.56 and 0.06 kg ha^{-1}, respectively (European Environment Agency, 2016).

2.4. Life cycle impact assessment

The life cycle impact assessment of herbaceous crop cultivation was determined by the ReCiPe Midpoint (H) method. The mid-points of eight categories of environmental impact, closely

connected to agricultural production in the region were selected: climate change in carbon dioxide (CO_2) equivalents, human toxicity in 1,4-dichlorobenzene (1,4-DB) equivalents, particulate matter formation in particulate matter 10 μm (PM10) equivalents, terrestrial acidification in sulphur dioxide (SO_2) equivalents, freshwater eutrophication in phosphorus (P) equivalents, terrestrial ecotoxicity and freshwater ecotoxicity (both in 1,4-dichlorobenzene (1,4-DB) equivalents) as well as fossil depletion in crude fossil oil (oil) equivalents. The ReCiPe impact categories were narrowed down based on other studies on perennial crops (Dressler et al., 2012; Bessou et al., 2013). Moreover, the results of normalisation were taken into account, which showed which impact categories are significant in the scenarios under study. After entering inputs and outputs to the SimaPro program, calculations were made of the environmental impact (characterisation). In order to compare which categories of impact had the most adverse effect on the environment during the production of Virginia mallow biomass, they were reduced to the same unit by normalisation (Europe ReciPe H/H).

3. Results and discussion

3.1. Characterisation results

3.1.1. Base scenario production without fertilisation (control)

Cultivation of Virginia mallow with no fertilisers was taken as the base scenario (control) in the study, because lignocellulosic crops should be produced with the minimum environmental impact, especially in regard to climate change.

The base scenario for cultivation of Virginia mallow showed that GHG emission per 1 Mg of dry matter was 95.94 kg CO_2 eq. (Table 4). The highest impact on GHG emission (68.4%) was found for emissions related to the depletion of organic matter from soil (Fig. 2). Much smaller impact on climate change was determined for the plant harvest (15.4%). The impact on human toxicity was 3.58 kg 1,4-DB eq. Mg^{-1} d.m., and chemical weeding had the most adverse impact, which accounted for 48.7% of this impact category. Biomass transport to the farm accounted for nearly ¼ of human toxicity and harvest accounted for 15.7%. The particulate matter formation in the cultivation of Virgina mallow was found to be 0.7 kg PM10 eq. Mg^{-1} d.m., with field emission accounting for 81.2%. Such a high impact was mainly attributable to the emission of particulate matter from the operation of machines in cultivation measures and harvest. The use of fuel alone, which was the second largest impact during the crop harvest, caused the emission of 0.068 kg PM10 eq, which accounted for just under 10% of this category of impact (Table 4, Fig. 2). The production of 1 Mg of dry biomass at the control plot was accompanied by the emission of 0.26 kg SO_2 eq. Mg^{-1} d.m. (impact on terrestrial acidification). Biomass harvest accounted for nearly 52% of this category of impact, followed by plantation liquidation. These emissions were closely connected with the use of diesel oil at these stages of production of Virginia mallow. Total emission in the freshwater eutrophication category amounted to 0.0034 kg P eq. Mg^{-1} d.m. Since no fertilisers were applied in the base scenario, the largest share in this category (61.4%) was found for the use of total herbicide to weed the plantation in the year when it was set up. Biomass transport accounted for nearly 21% of the impact in this category. The other stages of production of Virginia mallow accounted for less than 10% of impact on freshwater eutrophication. The use of a non-selective herbicide had the greatest share in the terrestrial and freshwater ecotoxicity (output: 0.006 and 0.19 kg 1,4-DB eq. Mg^{-1} d.m., respectively): 51.4% and 80.2%, respectively (Table 4, Fig. 2). Emission from the use of diesel oil during harvest accounted for 1/5 of the category impact on terrestrial ecotoxicity. Diesel oil use in biomass harvest had the greatest adverse impact on fossil depletion, whose total amount was 10.48 kg oil eq. Mg^{-1} d.m. (48.6% of this category). Other stages with a considerable contribution in this category were also associated with the use of diesel oil. However, their contribution to the impact was much smaller: 2.59–12.9%, for disking and plantation liquidation, respectively (Table 4, Fig. 2). It can be concluded that the main contribution to the environmental impact in the base scenario is caused by field emissions in two categories: climate change and particulate matter formation. Non-selective herbicide and the use of fuels for agricultural operations and transport dominated in the other impact categories.

3.1.2. Production of Virginia mallow with fertilisation

Fertilisation of a Virginia mallow plantation can have a beneficial effect on the crop yield (Table 3), which can reduce emission per 1 Mg of biomass collected from the same unit area, as well as per 1 GJ of energy obtained from biomass. Emission of GHG in the base scenario amounted to 95.94 kg CO_2 eq. Mg^{-1} d.m. or 5.3 kg CO_2 eq. GJ^{-1}. A more beneficial effect on climate change was observed for cultivation with dried and torrefied digestate (Fig. 3). When torrefied digestate was used at both rates, emission of CO_2 eq. was lower by 37% and 86% relative to C, for TD 85 and TD 170, respectively. The use of DD 85 resulted in very low impact on GHG emission (3.0 kg CO_2 eq. Mg^{-1} d.m. or 0.2 kg CO_2 eq. GJ^{-1}), whereas increasing the rate to 170 kg ha^{-1} N contributed to negative GHG emission (−24.7 kg CO_2 eq. Mg^{-1} d.m. or −1.4 kg CO_2 eq. GJ^{-1}). In this case, sequestration of soil carbon more than compensated for

Table 4
Environmental impact of Virginia mallow production (base scenario: control) expressed per 1 Mg of biomass dry matter.

Impact category	Unit	Total	Chemical weeding	Disking	Winter ploughing	Harrowing	Planting	Mechanical weeding	Harvest	Transport	Plantation liquidation	Field emissions
Climate change	kg CO2 eq.	95,94298	1,4000658	0,783874	2,55763	0,977661	1,227313	1,84097	14,73037	2,913517	3,897548	65,61404
Human toxicity	kg 1,4-DB eq.	3,5818	1,7432353	0,029863	0,074395	0,037246	0,0357	0,070135	0,561139	0,881602	0,148484	0
Particulate matter formation	kg PM10 eq.	0,700405	0,00259654	0,003622	0,011817	0,004517	0,005671	0,008506	0,068056	0,009191	0,018008	0,568421
Terrestrial acidification	kg SO_2 eq.	0,259017	0,00606575	0,007136	0,023283	0,0089	0,011172	0,016759	0,134086	0,016135	0,03548	0
Freshwater eutrophication	kg P eq	0,00337	0,00207015	1,8E-05	5,87E-05	2,24E-05	2,82E-05	4,23E-05	0,000338	0,000702	8,95E-05	0
Terrestrial ecotoxicity	kg 1,4-DB eq.	0,005957	0,00305896	6,53E-05	0,000411	8,14E-05	0,000197	0,000153	0,001226	0,000439	0,000324	0
Freshwater ecotoxicity	kg 1,4-DB eq.	0,190551	0,15288724	0,000624	0,002047	0,000778	0,000982	0,001466	0,011727	0,016937	0,003103	0
Fossil depletion	kg oil eq.	10,48469	0,52543986	0,271074	0,884462	0,338088	0,424421	0,636631	5,093956	0,962795	1,347823	0

the direct and indirect GHG emission. Carbon sequestration in DD 85, DD 170, TD 85 and TD 170 resulted mainly from large rates of organic fertilisers and high organic matter content. C input to soil from DD and TD at these plots ranged from ca. 2.5–5.6 Mg ha^{-1} C. However, for WD it was only 0.75–1.5 Mg ha^{-1} C, and in MF – zero. Interestingly, despite smaller amounts of TD transported to the field (with related lower machines use) and higher carbon content in this fertiliser, lower GHG emission compared to DD could not be achieved. It was caused mainly by higher biomass yield per 1 ha with DD than with TD, as well as by additional input related to torrefaction of the fertiliser. The application of the other fertilisation methods and rates increased the impact on climate change compared to C. Higher emission of carbon dioxide equivalents were noted for MF 170 (nearly 5 times more), MF 85 and WD 85 (nearly 3 times more) as well as WD 170 (nearly 2 times more) than for the base scenario. Therefore, it is reasonable to claim that the

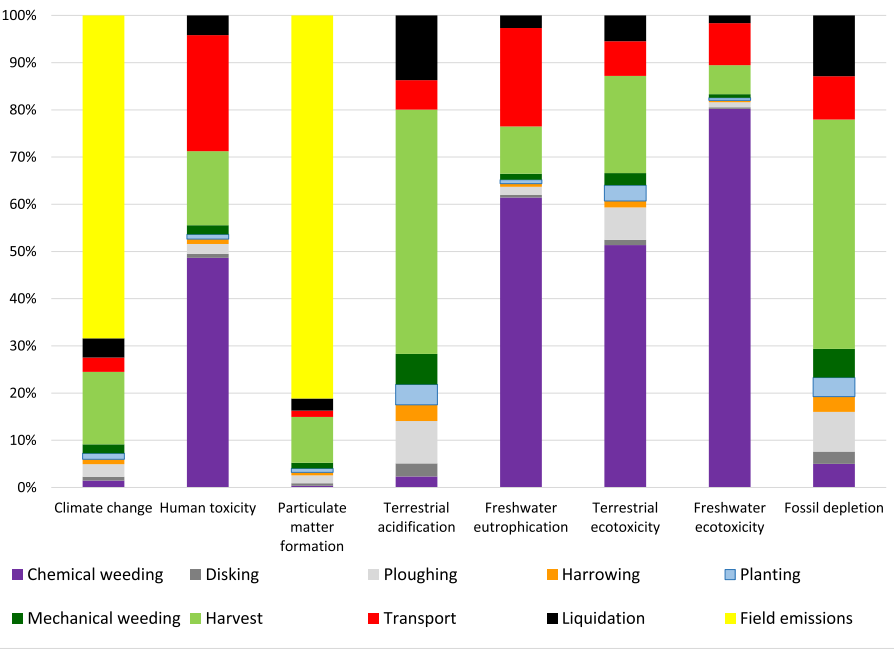

Fig. 2. Contribution of production processes for 1 Mg of dry biomass production for the base scenario (control).

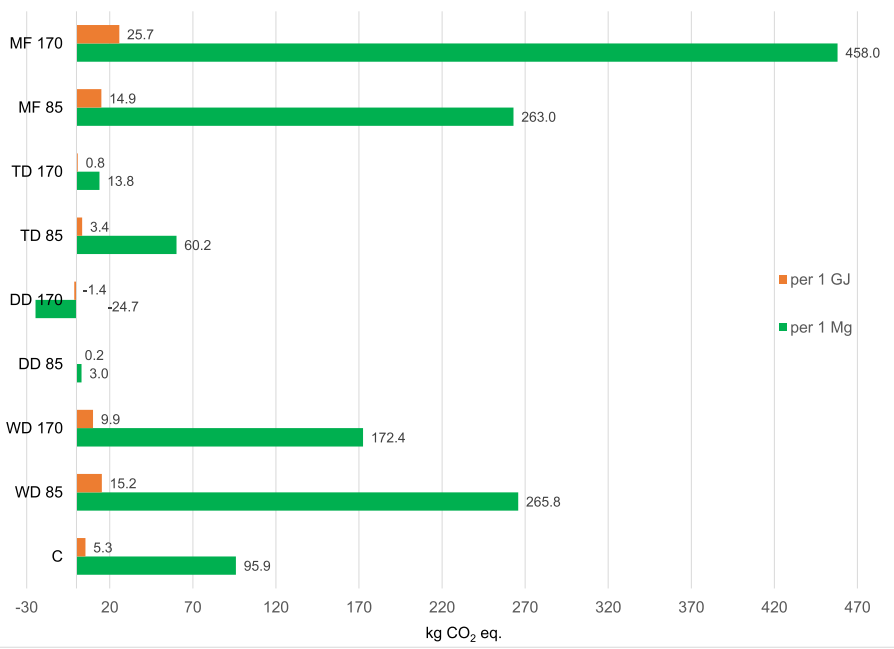

Fig. 3. Emission of GHG per 1 Mg d.m. and 1 GJ from production of Virginia mallow for the fertilisation options under study.

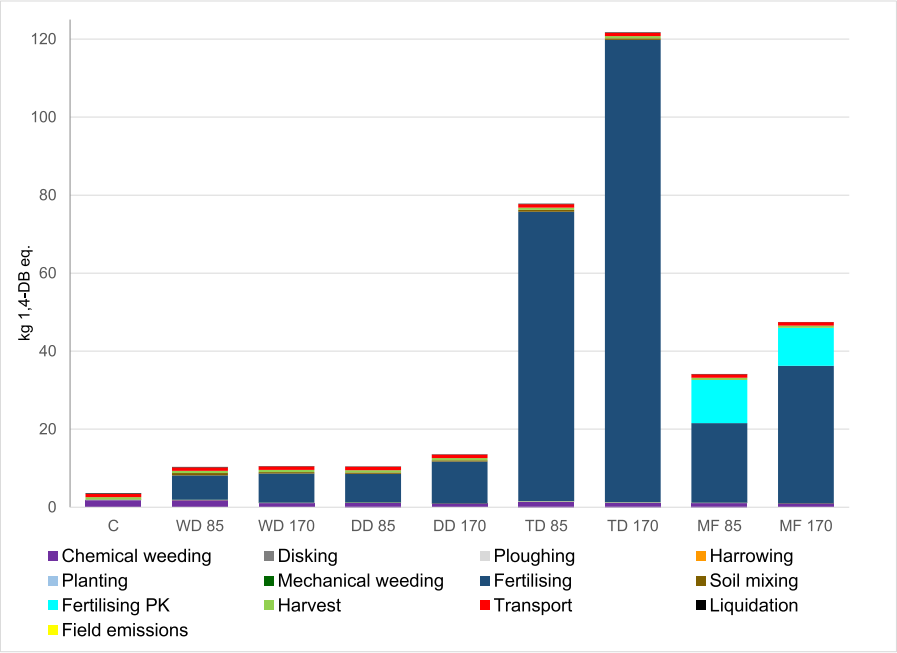

Fig. 4. Human toxicity (kg 1,4-DB eq.) of production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

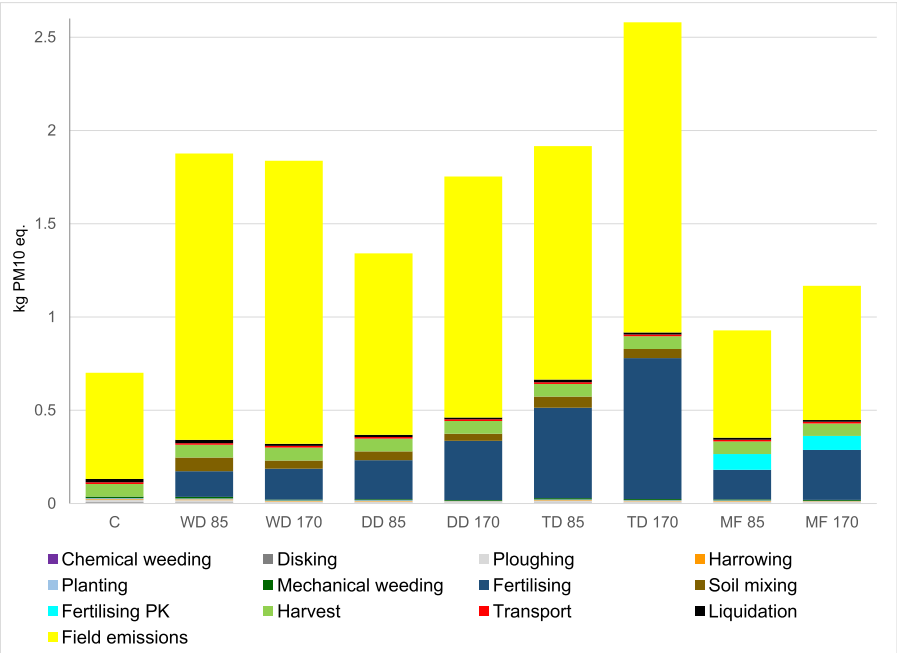

Fig. 5. Particulate matter formation (kg PM10 eq.) in the production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

application of dried and torrefied biogas residue has a beneficial impact on crop yield and emission of GHG from biomass production compared to non-fertilised plants and those fertilised with more expensive mineral fertilisers. In other studies on the production of perennial crops, the emission of CO_2 eq. was also found to range widely. Krzyżaniak et al. (2016b) found GHG emission to range from 19 to 97 kg CO_2 eq. Mg^{-1} d m and to depend on the yield of various varieties of short rotation coppice (SRC) willow (average from the experiments 36 kg CO_2 eq. Mg^{-1} d m or 2.12 kg CO_2 eq. GJ^{-1}). Other studies on willow have shown that GHG emission can also be negative (from −2.7 to −6.9 kg CO_2 eq. GJ^{-1}), which is caused by large carbon sequestration in soil (Goglio and Owende, 2009). GHG emission for poplar SRC as found in other studies indicated that GHG emission can be negative (−0.468 kg CO_2 eq. Mg^{-1} d.m.) (Bacenetti et al., 2012) or positive and it was close to the base scenario result in our study (96 kg CO_2 eq. Mg^{-1} d.m.) (Manzone and Calvo, 2016). Research conducted by (Borzecka-Walker et al., 2011) showed the emission of GHG generated from miscanthus biomass to be approx. 225 kg CO_2 eq. Mg^{-1} d.m. Compared to the emission of GHG in maize cultivation, i.e. an annual crop with a

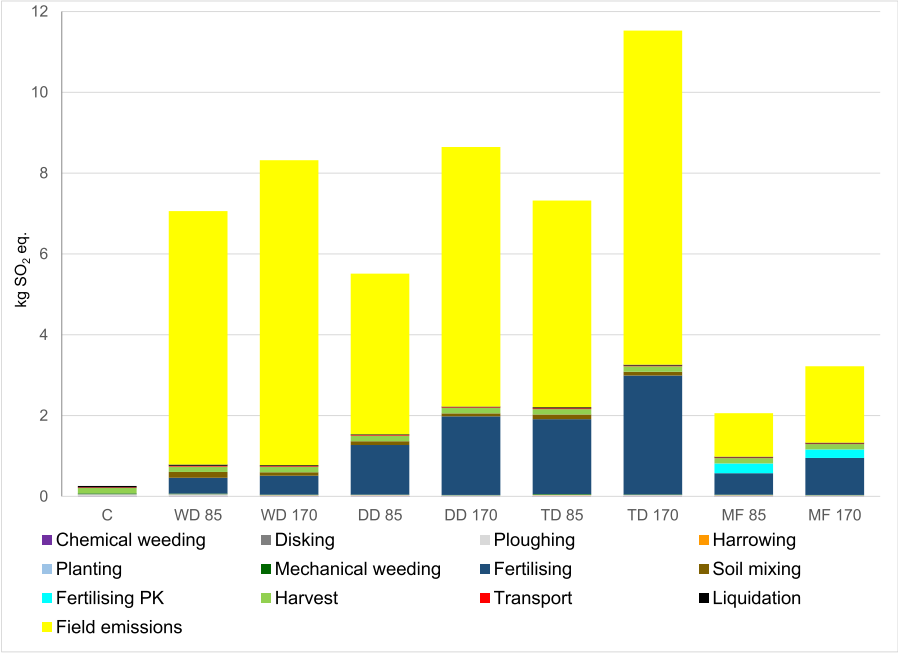

Fig. 6. Terrestrial acidification (kg SO_2 eq.) in the production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

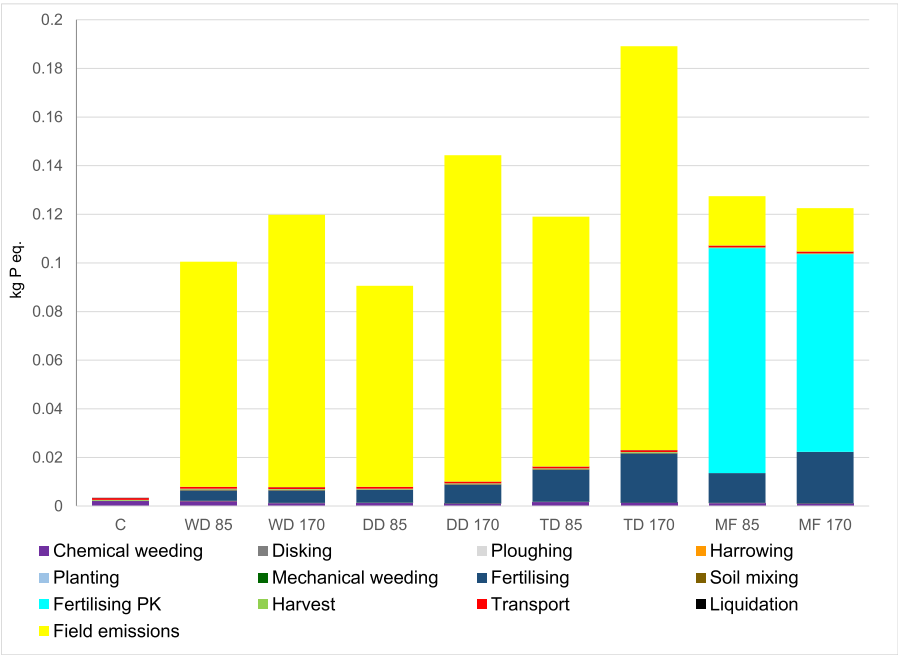

Fig. 7. Freshwater eutrophication (kg P eq.) in the production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

high biomass yield per ha ranged – according to various authors – from 152 to 315 kg CO_2 eq. Mg^{-1} d.m. (Dressler et al., 2012; Manzone and Calvo, 2016; Parajuli et al., 2017b).

All of the fertilisation options had a more adverse effect in the human toxicity category than the base scenario (C) (Fig. 4). Fertilisation with WD and DD at both rates was the least adverse to the environment compared to C, although emission of 1,4-DB eq. was three to four times higher. The use of MF 85 and MF 170 resulted in 9- and 13-times higher effect on human toxicity than C, respectively. The most adverse effect on the environment was observed when TD was used at both rates. The effect in this category was nearly 22 and 34-times higher compared to C, for TD 85 and TD 170, respectively (Fig. 4). Such a great difference compared to other fertilisers was caused by the demand for a large amount of energy for torrefaction of digestate and related ash disposal from wood.

Particulate matter formation was greater in all options of Virginia mallow cultivation compared to the base scenario (Fig. 5). The greater effect obviously resulted from the use of energy in fertiliser production, drying and torrefaction of digestate and from the use of machines in crop fertilisation. The lowest impact in this category

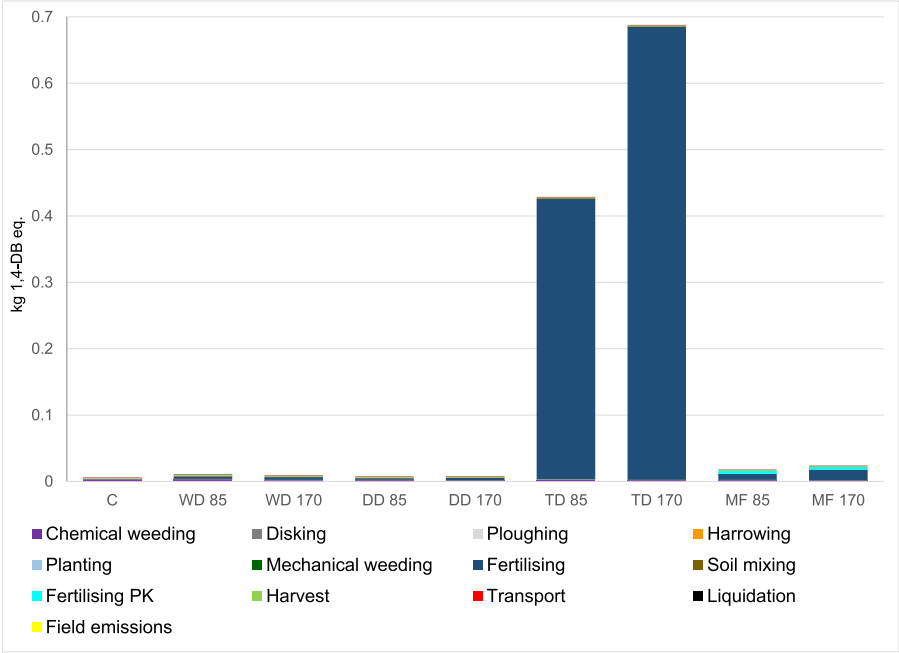

Fig. 8. Terrestrial toxicity (kg 1,4-DB eq.) of the production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

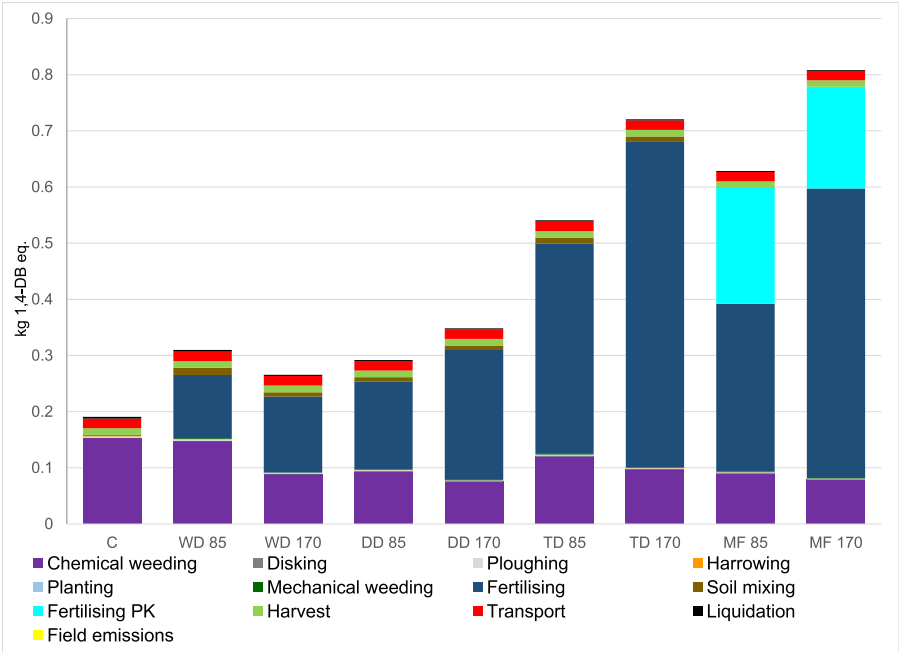

Fig. 9. Freshwater toxicity (kg 1,4-DB eq.) of the production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

compared to the base scenario was observed for MF 85 and MF 170, where the emission of PM10 eq. per 1 Mg d.m. was higher by 33% and 66%, respectively. The greatest impact in this category was observed for TD 170 (nearly 3.7 times greater impact than for C), which was caused by emissions from fuels used in the torrefaction of digestate.

The use of each fertilisation option had a more adverse impact on terrestrial acidification compared to the base scenario (Fig. 6). The lowest emission compared to C was found for variant MF 85 (eight times greater environment impact) and the greatest was for TD 170 (more than 44 times higher). The greatest impact of TD was caused by high field emission of nitrogen compounds, but also by higher input for the fertiliser production. The acidification potential in the cultivation of SRC willow was 0.59 kg SO_2 eq. Mg^{-1} d.m. (Krzyżaniak et al., 2016b). Higher emissions were observed for the production of maize – ca. 0.91 kg SO_2 eq. Mg^{-1} d.m. – and wheat with mineral fertilisation applied at a similar level as in our study: 1.10–1.32 kg SO_2 eq. Mg^{-1} d.m. (Brentrup et al., 2004; Dressler et al., 2012). The results were lower than in our study, which was caused by a lower yield of Virginia mallow per 1 ha than other types

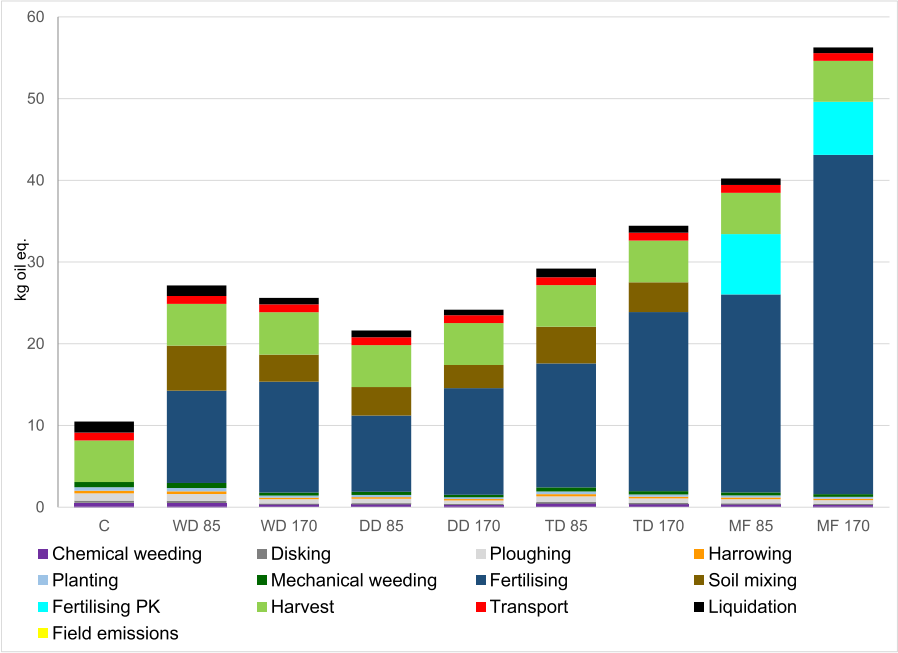

Fig. 10. Fossil depletion (kg oil eq.) for the production of 1 Mg d.m. of Virginia mallow depending on the fertilisation option.

of biomass in other studies, as well as a high impact of digestates used.

The use of fertilisers, both digestates and mineral ones, resulted in an increase in the impact of the production of 1 Mg of dry Virgina mallow biomass on freshwater eutrophication; 30–56 -fold compared to the base scenario (Fig. 7), for DD 85 and TD 170, respectively. The application of a higher (170 kg ha^{-1}) nitrogen rate in fertilisers produced from digestate resulted in an increase in the amount of phosphorus supplied to the field with fertilisers, which, in consequence, resulted in increased eutrophication. Moreover, the production of torrefied digestate resulted in the production of ash from wood chips (which contained phosphorus) burned during the torrefaction process; this also increased the level of freshwater eutrophication. However, the greatest effect in this category in mineral fertilisers was observed not only for field emissions from fertiliser use, but also the production of phosphorus fertilisers. These results for eutrophication indicate that cultivation of Virginia mallow in the base scenario had a smaller effect in this category than cultivation of annual and perennial plants. However, the use of fertilisation in Virgina mallow cultivation, and particularly high rates of digestate, considerably increased eutrophication compared to other studies on perennial plants. Therefore, the effect on eutrophication of fertilisation options was similar to maize, spring barley and ryegrass (ca. 0.14–0.19 kg P eq. Mg^{-1} d.m.) (Brentrup et al., 2004; Krzyżaniak et al., 2016b; Parajuli et al., 2017a; Parajuli et al., 2017b).

Production of Virginia mallow with fertilisation had a greater impact on terrestrial ecotoxicity compared to C but the emissions from all WD, DD and MF options were not significantly higher and ranged from 0.008 to 0.024 kg 1,4-DB eq. Mg^{-1} d.m., for DD 85 and MF 170 (Fig. 8). However, torrefaction of digestate resulted in extra consumption of heat and electricity, with a consequent over 71–115 increase, compared to C, in the effect of variants TD on terrestrial ecotoxicity. It was found in other studies that the production of SRC willow (average from various varieties) had a 10-times greater impact on terrestrial ecotoxicity compared to the production of Virginia mallow, except in both variants of TD. The impact of Virginia mallow in these options was greater than for the better-yielding willow varieties and was similar to those which were lower-yielding (range from 0.139 to 0.487 kg 1,4-DB eq. Mg^{-1} d.m.) (Krzyżaniak et al., 2016b).

The effect of methods and rates of fertilisation on production of Virginia mallow biomass in the freshwater ecotoxicity category was higher by 39–324% compared to the base scenario, for options WD 170 and MF 170, respectively (Fig. 9). The largest impact in this category in the WD 170 option was observed for inputs related to the production and use of agricultural machines to scatter fertiliser in the field and the use of a total herbicide in the year of setting up the plantation. On the other hand, the greatest impact on freshwater ecotoxicity in option MF 170 was observed in the production of mineral fertilisers NPK, especially ammonium nitrate.

Fossil depletion for production of Virginia mallow with fertilisation was from two to five times higher compared to the base scenario, for DD 85 and MF 170, respectively (Fig. 10). The largest fossil depletion in the DD 85 option was caused by the use of diesel oil in the crop harvest, as well in fertilisation and mixing soil with fertilisers. However, in the MF 170 option, the greatest impact in this category was observed for the consumption of fossil fuels in the production of ammonium nitrate and much smaller in the production of triple phosphate and the use of fuels for agricultural machines.

3.2. Normalisation results

Fig. 11 shows the life cycle impact assessment (LCIA) results expressed in units per dry tonne of Virginia mallow biomass normalized using ReCiPe's European hierarchical version. The impact category with by far the highest normalized score was freshwater eutrophication. Variants TD 170 and DD 170 evidently stood out in this category. The second largest impact was found for terrestrial acidification and the greatest effect was observed for option TD 170. Although the effect of the human toxicity category was lower on average than particulate matter formation, the application of option TD 170 in the first category was higher than

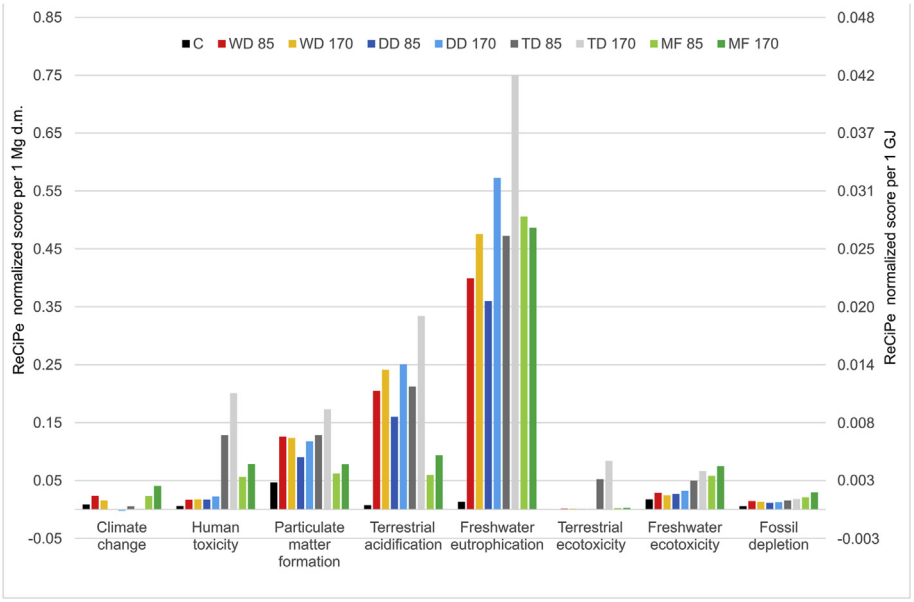

Fig. 11. Results of normalisation of Virginia mallow production, using the ReCiPe midpoint impact assessment method (hierarchical version with European normalisation).

the combined effect of the impact of all cultivation options in the latter category. These findings are consistent with those of other studies in crop production. The highest normalized score in a study conducted by Chatzisymeon et al. (2017) was freshwater eutrophication. However, a larger effect of freshwater and human ecotoxicity than acidification was observed in the quoted study than in the current study. The higher toxicity was caused by as many as six chemical procedures for pest control in strawberry production. Chemical spraying (herbicide) was done only once in the current study. Similar results were obtained by Harris et al. (2016) and Krzyżaniak et al. (2016b). In those studies, the use of plant protection products also resulted in high toxicity, with a high impact of eutrophication and acidification. Normalisation of the current results shows that use of large rates of fertilisers may not be justified when the biomass yield increase is small. It must be noted that since Virginia mallow is grown as an energy feedstock or a raw material for biorefineries, an impact assessment in the climate change category was important for this species. The outcome of normalisation indicates that the environmental impact in this impact category was negative for DD 170. The impact of mineral fertilisation was noticeably higher compared to the other fertilisation options, although, in general, the climate change impact was low compared to the other impact categories. The relationships shown in Fig. 11 were the same for normalisation results when expressed per 1 GJ, although the values were ca. 17 times smaller (due to recalculation of normalisation score to biomass energy content).

4. Conclusions

The application of biogas digestate can increase the yield of lignocellulosic crops. This was the case with the production of Virginia mallow biomass. Considering the production of this species as feedstock for biofuels, low impact on climate change category can be noted for non-fertilisation option. The use of dried digestate at lower rate and torrefied digestate at both rates resulted in a significant decrease in greenhouse gas emissions compared to the base scenario. The application of dried digestate at higher fertilisation rate resulted in carbon sequestration in the soil. On the other hand, the fertilisation options affected the environment more than the base scenario in the other impact categories. The application of WD and DD at lower rates could be recommended for Virginia mallow instead of mineral fertilisers, whereas DD 170 and TD at both rates had the most adverse environmental effect. These fertilisers may have increased the yield and allowed for sequestration of carbon in soil, but their high content of phosphorus and high energy consumption for their production (drying and torrefaction) had an overall adverse effect. Moreover, our findings suggest that using fertilisers at a rate equivalent to 170 kg ha^{-1} N may not be justified because of a high impact on freshwater eutrophication and acidification.

Therefore, a solution should be sought to decrease the negative environmental impact of fertilisers produced from digestate. For example, the production impact could be decreased by increasing the use of low-emission energy sources to produce torrefied digestate. On the other hand, lower rates of DD and TD could be used to increase the use of phosphorus and the deficient nitrogen could be supplied with other fertilisers (e.g. mineral). Such a procedure could also affect the current issue of utilising digestate and reduce the operating cost of a biogas plant and crop production. These also require further studies.

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